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Density, some anatomical properties and natural durability of stem and branch wood of two tropical hardwood species for ground applications

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Abstract As wood resources deplete, branchwood is being promoted to supplement stemwood in Ghana, but its natural durability, which indicates its service life and can influence its acceptance and use is scarcely studied. This study compares the natural durability and some anatomical properties of branchwood and stemwood of *Entandrophragma cylindricum* (sapele) and *Khaya ivorensis* (mahogany) using *Ceiba pentandra* stemwood as control. Natural durability test followed field test method according to European Standard EN 252 1989 in combination with percentage weight losses while the anatomical investigations followed IAWA Committee 1989 recommendations. For each species, two branch logs were cut from each of two sampled trees from two natural forests in Ghana. Stemwood was also obtained from the same forest reserves as the branches. All sample groups were tested at air-dried moisture content of 14 ± 2 % as specified in the standard. Branchwood of both species were denser than their stemwood, but in addition to mahogany stemwood they were rated "non-durable", while sapele stemwood was rated moderately durable. Thus at 5 % significance level, natural durability of mahogany branchwood appeared comparable to that of its stemwood whereas sapele branchwood was significantly less durable than its stemwood but more durable than Ceiba stemwood. Branchwood and stemwood vessels diameter and proportion also were significantly different ($p < 0.1$). Expectedly, density correlated positively with natural durability, but the correlation among anatomical properties, natural durability and density were stronger in stemwood than in branchwood. In conclusion, stem and branchwood of mahogany are both non-durable but sapele stemwood appears better than its branchwood for ground applications. Anatomical properties of stemwood influenced natural durability more than those of branchwood. For better acceptance of branchwood of the species for wood products manufacturing, further research would be necessary for additional data on their toxic extractive levels, mechanical properties and durability at different sites or/and using other drying methods.

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1 Introduction

Timber products in Ghana including garden furniture are major economic resources that contribute substantially to the gross domestic product (GDP) of the country. Timber export is the third foreign exchange earner after cocoa and minerals and a decade ago, it contributed about 8 % to the GDP of the country (Ministry of Lands and Natural Resources-MLNR 2012). This contribution has, however, fallen to a current level of 4 % and the situation is partly attributed to the dwindling trend of the wood resources which stands at a mean rate of 2 % per annum (MLNR 2012). Besides the national GDP, wood products manufacturing also provides direct employment to over 100,000 people (Agyarko 2001), and together with indirect employments, the forests provide livelihood to nearly 15 % of the Ghanaian population (Ministry of Lands and Natural Resources-MLNR 2012). It is also reported that the deforestation rate in Ghana is estimated at 750 km^2 per year and translates into about €877,346.903 loss in revenue (World Bank 1988). The continuous deforestation situation, among other factors, has caused some wood processing industries to either fold-up or not operate at full capacity due to lack of raw materials leading to job losses. Therefore it is evident that, since timber resources are major factors in wood products industries' operations, the dwindling trend is not only negatively affecting the GDP of the country but also the general economic lives of a lot of people and their dependants.

The most disturbing aspect of the depletion of Ghana's forests is the drastic extinction of the commercial and the most valued timber species used for furniture and other value-added products for both domestic and export markets (Dadzie 2011). According to the International Institute for Environment and Development (IIED), supplies of the traditional (premium and commercial) hardwood timber species including *Entandrophragma cylindricum* (sapele) and *Khaya ivorensis* (mahogany) could fall by a further 50 % within 5 years (Acquah and Whyte 1998). This could lead to further shortage of timber to feed the furniture, construction and other wood related industries and could lead to eventual collapse of additional number of such industries. Meanwhile, economically, garden furniture made from mahogany and the mixed-redwoods (which include sapele) command comparatively high monetary value in the export market. In fact, furniture from such wood can yield additional income of about 200–385 % higher than their corresponding lumber export value (Dadzie 2011).

Due to the foreseen consequential threat of wood raw material extinction to the future of wood and construction related industries in particular and human activities and livelihood in general, researchers are exploring the use of branchwood of tropical hardwood as supplements to their stemwood. However, studies on branchwood have covered some physical, mechanical and some workability properties of some Ghanaian hardwoods. For instance, Okai (2002) studied some physical and mechanical properties of *Terminalia ivorensis* (emire) and *Aningeria robusta* (asanfena). Okai (2003) also worked on the workability of emire and asanfena and successfully used some in furniture production. Amoah et al. (2012) also studied the mechanical and physical characteristics of branchwood and rootwood of emire and *Milicia excelsa* (iroko/odum).

Among the wood species in Ghana, *E. cylindricum* (sapele) and *K. ivorensis* (mahogany) are some of the finest woods in terms of workability and aesthetic properties making them among the most preferred wood used for furniture production for both domestic and export markets (Pleydell 1994). Sapele and mahogany trees also have branches of about 25 and 64 % respectively per their tree volumes (Dadzie 2013), which could be used as alternatives or supplements to their stemwood in new value-added products, like garden furniture. However, for producers and consumers to accept branchwood better, some properties specific to the intended application in comparison with stemwood of the species should be known and understood (Gurau et al. 2008). One of these properties that could supply stakeholders in the wood products manufacturing industry with added value information towards addressing the most appropriate use of the material is its natural resistance to biological deterioration (natural durability). Natural durability property of wood is necessary because it gives indication of the capability of the wood material, in its natural state (i.e. without any preservative treatment), to withstand wood-destroying organisms and also predict the service life of a product made from that wood (Palenti et al. 2011). Service life of wood is important because, despite the versatility of wood as constructional material, it is being superseded in several areas where other expensive materials such as metals, concrete, plastics, ceramics, etc. are emerging as preferred materials for use, even when the initial cost benefit favours the use of wood, all due to uncertainty about the long-term resistance of some wood to the natural processes of degradation by biological agents (Eaton and Hale 1993). It is however reported that knowledge of wood natural durability property is of much importance in deciding whether some wood can be used for outdoor and ground applications, like garden furniture, fence posts etc. since they will be exposed to many wood destroying agents (Palenti et al. 2011; Brischke and Rolf-Kiel 2010).

Density gives a measure of how much actual substance is inside a specific wood and greater density means more structural material, which tends to make the wood stronger, harder and naturally durable (Skadsen 2007). It is also reported that density of wood is a measure of the amount of cell wall per unit volume or the proportion of the void volume which is directly related to its porosity and all consequently affect the durability of wood (Haygreen and Bowyer 1996). Relating to these findings, Antwi-Boasiako and Pitman (2009) however found both positive and negative relationships between density and natural durability of some hardwood stemwoods. However studies that compare the natural durability qualities of branchwood of sapele and mahogany with their stemwood as well as those that assess the influence of density and anatomical properties on branchwood durability are either scarce or unpublished and therefore appear unavailable. Density is also influenced by the anatomical properties of wood, but the anatomy of branchwood of Ghanaian hardwood species also appears unavailable, and as a result Okai (2002) recommended such investigations. It is therefore a necessity that in an effort to promote branchwood utilization the natural durability of wood species are investigated in addition to their relationships with density and anatomical properties.

As information on the natural durability and anatomical properties of the branchwood of Ghanaian tropical hardwood is not available, this present study was conducted to investigate the natural durability and some anatomical properties of the branchwood of sapele and mahogany compared to their stemwood to ascertain whether or not the branchwood can supplement their respective stemwood for ground or other outdoor applications like garden furniture (which is sometimes placed under trees and in gardens where parts of them are in direct contact with the soil and even go into it). The research questions to be answered in this study include: (1) How do density and natural durability of branchwood of sapele and mahogany compare with those of their stemwood counterparts and stemwood of *Ceiba pentandra*? (2) How do some anatomical properties of branchwood of the species compare with those of their stemwood counterparts and *Ceiba*? and (3) How do stemwood and branchwood density, natural durability and anatomical properties relate? Findings are expected to contribute towards the search for alternatives or supplements to stemwood which, according to Cionca et al. (2006) has become a top priority problem to stakeholders in the wood and related or dependent industries.

2 Materials and methods

2.1 Research design

The research compared the natural durability and some anatomical properties of stemwood of *Entandrophragma cylindricum* (sapele) and *Khaya ivorensis* (mahogany) to their branchwood using *Ceiba pentandra* (onyina) stemwood as control, by applying the soil block (field) test for a period of 12 months based on European standard EN 252 (1989). Quartey et al. (2008) and Quartey (2009) have acceptably evaluated the natural durability of some lesser known Ghanaian hardwood species within 6 months based on this standard EN 252 (1989). Moisture contents were measured with a moisture meter (MO210 designed to measure wood MC up to 44 %, as specified by the manufacturers) and which was found to have accuracy of ±2 % upon validation with oven-dry method using 20 samples drawn from stem and branch wood of the species (5 stem samples + 5 branchwood samples from each species). Some researchers including Beaulieu et al. (1987), Ayarkwa et al. (2000), and Amoah et al. (2012) have also acceptably used moisture meters in wood property studies.

The study measured natural durability in terms of percentage weight losses (%WL) and visual rating of the extent of destruction/attack by biological agents (also used to predict service life of wood). Weight loss was quantitatively measured on a 4-point percentage scale as: 0–5 % loss very durable; 6–10 % loss durable; 11–40 % loss moderately durable; and 41–100 % loss non-durable (Eaton and Hale 1993). The extent of attack was however, qualitatively measured on a 5-point visual rating scale according to EN 252 (1989) as: 0, No attack; 1, Slight attack; 2, Moderate attack; 3, Severe attack; and 4, Failure (completely destroyed).

The test site used for this study has medium to fine texture soil with pore spaces varying from 40–60 % and it is home to a lot of termite mounds (Kumi-Woode 1996). The site also has temperature range from 21.5 °C to 30.7 °C and average humidity of about 84.16 % at 0900 GMT and 60 % at 1500 GMT. There is also a double maximum rainfall regime (214.3 mm in June and 165.2 mm in September) which has direct effect on the environment, including soil organisms' activities and agriculture. As a result, it is reported that the site is generally a very high decay hazard zone that has high decay index (Ministry of Local Government and Rural Development and Maks Publications and Media Services 2006; Ministry of Food and Agriculture 2013; Kumi-Woode 1996).

The study also examined, quantified and compared some selected anatomical properties (vessel lumen diameter, vessel, fibre and total parenchyma proportions) in stem and branch wood of the test and control species in accordance with IAWA committee protocol (1989).

2.2 Samples collection and preparation

2.2.1 Natural durability test

Two branch logs of each species were extracted from two trees from two natural forest reserves within two ecological zones of Ghana. The forest reserves were Asukawkaw reserve at Awronsua near Nkawkaw in the Eastern Region which is within the boundaries of longitude 0°1°W and latitude 6°7°N (a moist semi-deciduous-South East type forest) and Suie reserve at Nsawora near Sefwi Wiawso in the Western Region which is within the boundaries of longitude 2°3°W and latitude 6°7°N (a moist evergreen forest). All two reserves are concessions of Logs and Lumber Limited (LLL)—a timber processing firm in Kumasi, Ghana. Because these reserves are natural forests, the age of the trees was not known. However, in all, 8 straight branch logs with diameters ranging from 26 to 52 cm and lengths from 1.5 to 2 m were extracted from the first and third branches of each tree to obtain varied diameters of branchwood for the study. The main criterion for a sample to be taken from the first and the third branch was straightness with a view to avoid the inclusion of obvious tension wood. The species' stemwood samples and those of the control species were obtained from the firm's factory premises (as it was not possible to obtain some from the forests) but all of them were from logs from the same forest reserves where the branch logs were extracted. Samples from two stem logs from each of the forest reserves were taken. Hence stemwood samples were also taken from 4 logs (2 logs for each species).

All the branch logs were conveyed from the forests to LLL for processing. Both through-and-through and quarter sawn methods were used for the conversion of the logs to lumber, using the same vertical bandmills that are being used for the conversion of logs in the factory. The logs were initially processed into rough lumber boards of 25 mm thickness with varied widths and to the lengths of the logs, while removing all sapwood first (sapwood in the studied hardwoods have clearly light colour which is very distinct from the heartwood and so sapwood separation did not need any special method). After the conversion, both branch and stem boards were re-sawn and crosscut into dimensions of 25 mm × 60 mm × 420 mm and grouped according to the two trees and the two reserves from which they were obtained hence obtaining 8 groups, (i.e. 2 species × 2 trees × 2 reserves). Clear heartwoods free of knots and other visible defects such as woolly or fuzzy surfaced pieces were then sampled from each group (since fuzzy and woolly surfaced wood are clear evidence of tension wood- Eaton and Hale 1993; Tsoumis 1991). Afterwards both branch and stem samples were regrouped into two each according to species, thus obtaining 4 groups in all [i.e. (1 stem group each × 2 species) + (1 branch group each × 2 species) = 4 groups]. All samples were conditioned in the air-drying shed of LLL to average MC of 14 ± 2 % at same temperature and relative humidity used by the company to air-dry wood. All samples were further prepared to final dimensions of 12.5 mm × 25 mm × 250 mm [modified dimensions of the prescription of European Standard EN 252 and acceptably used by Quartey et al. (2008); Quartey (2009)]. Though the standard EN 252 (1989) specifies ten (10) replicates of study specimens prepared to dimensions of [(500 ± 1) mm × (50 ± 0.3) mm × (25 ± 0.3) mm] when measured at 14 ± 2 %MC, it also recommends and accepts modifications of the specifications. The modification was done in order to have more samples to cover relatively wider plot as proposed and acceptably done by Feuntes-Talavera et al. (2011) who modified specimen dimensions and quantity in EN 350-1 (1994) so as to use more samples with reduced dimensions. The control samples (stemwood of *Ceiba pentandra*-onyina) were also air-dried and prepared to dimensions similar to the study/test specimens.

2.2.2 Anatomical properties test

Three 20 mm cubes subsamples were prepared for each wood type and species from each site/forest reserve totalling 24 cubes (i.e. 3 replicates × 2 wood types × 2 species × 2 sites). Samples were softened before sectioning with a sliding microtome, by placing them in water for 21 days followed by soaking in a mixture of ethanol and glycerol, in a ratio of 1:1 for a period of 21–30 days depending on species.

Thin sections of 20–30 µm thickness were cut from transverse surfaces of the samples using a sliding microtome. The sections were first washed in distilled water and then stained in 1 % safranin in 50 % ethanol solution for about 10–15 min. Afterwards, the sections were rewashed in distilled water and dehydrated in increasing concentration of ethanol from 30, 50, 70, 80, 90 and 100 % for 5–10 min. They were then immersed in xylene to remove little traces of water. The sections were then finally mounted permanently in Canada balsam and thereafter the slides were dried in an oven at 60 °C overnight. Photomicrographs were taken from the sections at 40× magnification using a light microscope (Micromaster Premier) with a digital camera.

2.3 Data collection

2.3.1 Density and natural durability

Sixteen replicates of study samples for each test species' branch and stemwood, and 16 control samples were used in this study. Thus for the two species and their two wood types, a total of 80 samples were used (16 replicates of stemwood of sapele and 16 of stemwood of mahogany, and another 16 replicates of branchwood of sapele and 16 replicates of branchwood of mahogany; and also 16 samples of control species) for the soil block test in accordance with EN 252 (1989). Though EN 252 specifies 10 replicates, it is important to note that, besides the fact that the standard itself accepts modifications, standard modifications have been acceptably done by previous researchers including Feuntes-Talavera et al. (2011) who modified specified specimen dimensions in EN 350-1 (1994) so as to use more samples with reduced dimensions. All samples were first weighed, given identification tagging and reweighed using electronic balance with accuracy of 0.01 g to note their initial weights or masses (W_1), whereas their dimensions were also determined with electronic vernier calliper with accuracy of 0.1 mm as specified in EN 252 and ISO 3131. Volumes and air dry density $\left(\text{measured as } \frac{\text{mass}}{\text{volume}}\right)$ were determined in accordance with ISO 3131.

On the field, the samples were planted to half of their lengths into the soil in rows and at distances of 300 mm between replicates and wood types of same species, but 600 mm between different species. Planting was done in rows in such a manner that the 4 sample groups alternated the formed rows. The control samples were however interspersed in the rows of the main test samples. According to Eaton and Hale (1993) and EN 252 (1989), regular inspection of stakes should normally be done every 6 or 12 months. But both Eaton and Hale (1993) and EN 252 (1989) recommend that this period can be modified depending on the country and the geographical area. In the light of this and considering the fact that the test site is a high decay zone with intense termite activities (Kumi-Woode 1996; Ministry of Food and Agriculture 2013), the samples or stakes were inspected at least once each 2 months while on the field to ascertain their states. After the samples had been in the soil for 12 months (during which time the control/reference samples have been replaced once and all have failed) they were carefully removed, carefully cleaned and conditioned to the initial MC range with the prevailing atmospheric relative humidity and temperature after which they were reweighed to obtain their final weights (W_2). The samples were also qualitatively assessed and visually rated in accordance with EN 252 (1989) in order to predict the species' service life.

2.3.2 Anatomical properties test

The micrographs were used to describe and qualitatively compare the anatomical features of stem and branch wood of the species by following the terminologies in IAWA committee's protocol (1989). Moreover, quantitatively, the anatomical properties were analysed from the photomicrographs using ImageJ software (National Institute of Health, Bethesda, MD, USA). For each wood type or species, vessel lumen diameters were obtained by taking 50 measurements (i.e. consisting of 25 measurements from specimens from each site/forest reserve) and finding the averages. In addition, for each wood type or species, proportions of the 3 main hardwood tissues [vessel, fibres, parenchyma (ray and axial)] were estimated using a total of 50 micrographs each (25 micrographs each of specimens from each forest reserve).

2.4 Data analyses

Data on density, weight losses, visual ratings and anatomical properties were analysed with both descriptive and inferential statistics. The percentage weight losses were calculated using the weights of specimens before planting ($\mathbf{W_1}$) and that after the test period ($\mathbf{W_2}$), by applying Eq. 1 (Nzokou et al. 2005; Eaton and Hale 1993);

$$\%\text{Weight loss} = [(W_1 - W_2)/W_1] \times 100\% \qquad (1)$$

The means and standard deviations of the data were subsequently determined. ANOVA was also used to determine significant differences in percentage weight losses and the anatomical properties among wood types as well as the effect of density and wood types on percentage weight losses using SPSS 17.0 version. Regression analyses using Excel 2003 and SPSS 17.0 versions were also employed to respectively determine the relationship between %WL and wood density (WD), and %WL, density and the selected anatomical properties.

3 Results and discussions

3.1 Density and natural durability

Table 1 presents the experimental results on density and natural durability on the basis of percentage weight loss and visual rating of stem and branch wood of the two test wood species and the control species.

From Table 1, branchwood of both species exhibited higher density compared with their stemwood counterparts. Branchwood of *E. cylindricum* and *K. ivorensis* were marginally higher in density than their respective stemwood counterparts by about 1 and 3.46 %, respectively. These appear to corroborate findings in literature that unlike softwood branchwoods, which generally have density of between 5 and 20 % lower than their stemwood counterparts, the branchwood of hardwood has density that ranges from higher in some species to lower or the same in others (Haygreen and Bowyer 1996; Tsoumis 1991). Moreover, branchwood density being higher than that of stemwood in hardwood seems consistent with previous studies (Okai 2002, 2003 who studied *Anigeria robusta* and *Terminalia ivorensis*; Amoah et al. 2012 who also studied stem, root and branch wood of *Terminalia ivorensis and Milicia excelsa*). It is noteworthy that the stemwood density values found in this study also appear to be within the range of findings previously reported on density of the studied species (Lemmens 2008; Duvall 2011; Kémeuzé 2008; Chudnoff 1984; Richter and Dallwitz 2000). Researchers have offered various reasons to explain the relatively higher density values in branchwood compared to stemwood (Fegel 1941; Patel 1970; Jane 1970; Haygreen and Bowyer 1996). It is reported that generally branchwoods grow more slowly and this makes them have shorter cells with thick cell walls that subsequently make them relatively heavier than stemwood (Bannan 1965; Fegel 1941; Patel 1970). Additionally, branchwood is known to contain reaction wood which also contributes to the higher density compared to stemwood (Tsoumis 1991).

Figure 1a, b is a graphical presentation of the percentage weight losses (%WL) and visual ratings of the wood species/types as indicated in Table 1.

From Eaton and Hale (1993) and EN 252 and as recorded in Table 1 and Fig. 1, the higher the %WL and

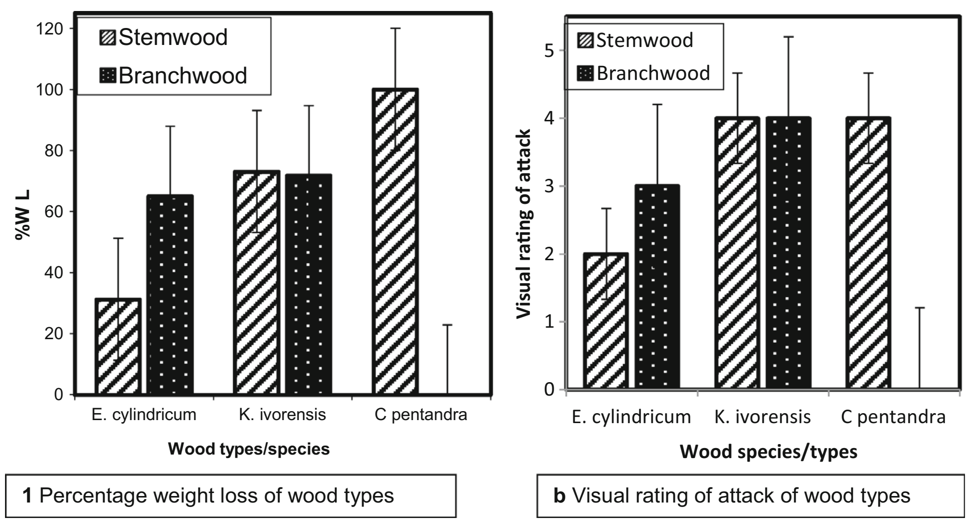
Table 1 Experimental result on density and natural durability of the stem and branch wood of sapele and mahogany with *Ceiba pentandra* (onyina) stemwood as control material

Species	Wood type	Density (Kg/m^3) Mean (SD)	% Weight loss Mean (SD)	F Value	*p* Value	Durability description according to % WL	Durability classes according to visual rating
Ceiba stem	Control	325 (33.81)	100.00 (0.00)^{ab}	20.358	0.000***	Non-durable	4
Entandrophragma cylindricum (sapele)	Stemwood	659 (25.64)	31.255 (33.03)^{ac}			Moderately durable	2
	Branch	665 (15.03)	64.980 (41.17)^{bc}			Non-durable	3
Ceiba stem	Control	325 (33.81)	100.00 (0.00)^{ab}	8.785	0.001***	Non-durable	4
Khaya ivorensis (mahogany)	Stemwood	549 (12.65)	73.188 (27.60)^{a}			Non-durable	4
	Branch	568 (6.12)	71.877 (24.79)^{b}			Non-durable	4

Mean values with the same letters indicate significant difference at 95 % confidence level

*** Significant at $p < 0.01$

Fig. 1 **a** Percentage weight loss and **b** visual rating of attack of control species (*Ceiba*), and stem and branch wood of test species (*Entandrophragma cylindricum* -sapele and *Khaya ivorensis* -mahogany)



visual rating of attack, the lower the natural durability and shorter service life of the wood type/species and vice versa. The control species had the highest %WL of 100 and was described as "non-durable" and also obtained visual rating of 4. In respect of the study species, sapele stemwood appeared to exhibit better natural durability (i.e. less %WL and less visual rating of attack) than its branchwood, but mahogany branchwood appeared comparable to its stemwood in terms of natural durability when both are air-dried to similar moisture content. Sapele stemwood had the least %WL of 31.26 and was described as "moderately durable" and obtained visual rating of 2, whereas mahogany stemwood obtained %WL as high as 73.19 % and was subsequently described as "non-durable" and obtained durability class of 4. Moreover, Tukey test indicated that the differences in natural durability of either stem or branch wood of the study species compared to the control species were statistically significant at 5 % level of significance (Table 1). Meanwhile, as was expected from the mean percentage weight losses, the natural durability (%WL) of stem and branch wood was significantly different ($p < 0.05$) for sapele but not for mahogany. These differences indicate that branchwood of sapele may not be a good substitute for its stemwood in ground applications. Moreover from this study, it appears that neither the stemwood nor the branchwood of mahogany could be used in ground applications owing to their low durability. Notwithstanding this, based on the apparent equality of the durability status of stem and branch wood of mahogany, it could be proposed that where the stemwood is applicable in terms of durability requirements, the branchwood could also be used as supplement.

Again, the results of the Tukey test (Table 1) also imply that at least branchwoods of both sapele and mahogany would have significantly higher natural durability than onyina stemwood upon in-ground or outdoor applications. Meanwhile, the durability descriptions obtained in the present study for the species (Table 1) appear to agree with previous studies that generally, sapele stemwood is moderately durable, whereas *Ceiba pentandra* (control species) is a non-durable or perishable wood within moisture content range of 12–15 % (Pleydell 1994; Kémeuzé 2008; Richter Dallwitz 2000; Duvall 2011; Chudnoff 1984). However, the non-durable description obtained by the stemwood of mahogany tends to disagree with previous studies which have described the species as moderately durable (Lemmens 2008; Pleydell 1994; Forest Products Laboratory 2010). This deviation however, could be attributed to the high termite activity of the high decay zone site used for this study (Kumi-Woode 1996), since mahogany is reported to be highly susceptible to termite attacks (Lemmens 2008; Chudnoff 1984).

Moreover, the visual rating of the extent of destruction (used for service life classifications) of 2, 3, and 4 (Table 1; Fig. 1b) respectively obtained for sapele stemwood, sapele branchwood and both mahogany stem and branch wood resulting from qualitative assessment indicated that, whereas the stem and branch wood of sapele may have service lives of 15–25 and 5–15 years, respectively, branch and stem wood of mahogany may have similar service lives of 0 to <5 years upon in-ground or outdoor application (National Association of Forest Industries—NAFI 2003; Cookson 2004). Hence for in-ground and outdoor applications like garden furniture, sapele stemwood appears to have relatively longer service life than its branchwood. However, sapele branchwood also appears to exhibit better resistance to biodeterioration (and can therefore have relatively longer service life) than stem and branch wood of mahogany as well as the control species. Therefore, at least, it could be proposed that sapele branchwood can be used instead of mahogany stemwood for in-ground applications especially at termite prone sites where mahogany is expected to be more vulnerable to early decay. The performance of mahogany in this study also indicates that, if the stem and branch wood of mahogany may be used for in-ground applications, preservative treatment may be necessary to extend their service life.

It is however worth noting that natural durability and or service life of wood used inside/indoors and above ground contact is expected to be better than when used in ground contact (NAFI 2003). Hence, although sapele branchwood was significantly lower in durability compared to its stemwood upon in-ground application, in terms of natural durability requirements, the branchwood could be a good supplementary material to its stemwood for indoor furniture and other indoor products where stemwood is being used for.

From the experimental results (Table 1; Fig. 1), it appeared that both wood species/type and density had some influence on the percentage weight losses (natural durability) and as such Two-way ANOVA (Table 2) was performed to provide further information in this respect.

Results from Table 2 indicate that both wood species/-type ($F = 30060$; $p = 0.000$) and wood density ($F = 7962$; $p = 0.000$) had significant effect on percentage weight loss (natural durability of wood). The interaction between wood species/type and density also had significant effect ($F = 74.116$; $p = 0.013$). However, from the adjusted R^2 value (below Table 2), wood species/types and wood density explained about 93 % of the variation in percentage weight losses (natural durability) of the stem and branch wood of the species.

The durability difference between branch and stem wood of sapele as well as the control species (onyina) might however also be attributable to differences in the proportions of the main anatomical structures (vessels, fibre and ray cells) of the two species which mostly determine wood density.

3.2 Anatomical properties test

Figure 2 shows the photomicrographs of the control species, and stem and branch wood of the test species. By observation, in general, vessels in both control species (*Ceiba pentandra*—C a), and both stem and branch wood of the test species (*Khaya ivorensis*—K.I a, b, and *Entandrophragma cylindricum*—E.C a, b) appeared to have rounded outlines but they are more in the test species than the control species. In addition, vessels of both stem and branch wood of the test species were observed to be partly solitary and partly in radial multiples of 2–4 with some occluded with deposits. Axial parenchyma appeared predominantly confluent paratracheal in stemwood.

Quantitatively, *Ceiba pentandra* (onyina) had the widest vessel lumen diameter of 227.21 μm but the vessel lumen diameters in branchwood compared to their respective stemwood were smaller by 7.54 % (sapele) and 7.47 % (*mahogany*) (Table 3). This appears to corroborate the findings of Bhat (1982) that vessels in branchwood are smaller than those in stemwood counterparts.

From Table 3, onyina exhibited the least percentage fibres of 17.69 % per 1 mm^2 cross-sectional area. However, fibre proportions of branchwood of sapele were higher by 1.28 % but that of mahogany was lower by 7.54 % relative to their respective stemwood. Moreover onyina obtained the highest percentage total parenchyma (ray + axial) of 72.93 %, whereas sapele and mahogany branchwood were respectively 0.77 and 1.25 % higher in total parenchyma than their respective stemwood counterparts. This appears to agree with Bhat (1982) that branchwood has relatively more parenchyma than stemwood. These findings also appear to generally agree with early findings that branchwood has relatively smaller vessel lumen diameter than the stemwood counterparts in most hardwoods, and that some kinds of cells are either more or less abundant in wood

Table 2 Two-Way ANOVA of percentage weight loss by stem and branch wood of the species

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	101235.043[a]	77	1314.741	1.207E4	0.000
Intercept	362756.803	1	362756.803	3.331E6	0.000
Wood species/type	3274.014	4	3274.014	3.006E4	0.000
Wood density	62428.260	72	867.059	7.962E3	0.000
Wood species/type* wood density	8.071	4	8.071	74.116	0.013
Error	0.218	2	0.109		
Total	473989.468	80			
Corrected Total	101235.260	79			

[a] R squared 0.980 (adjusted R squared 0.931)

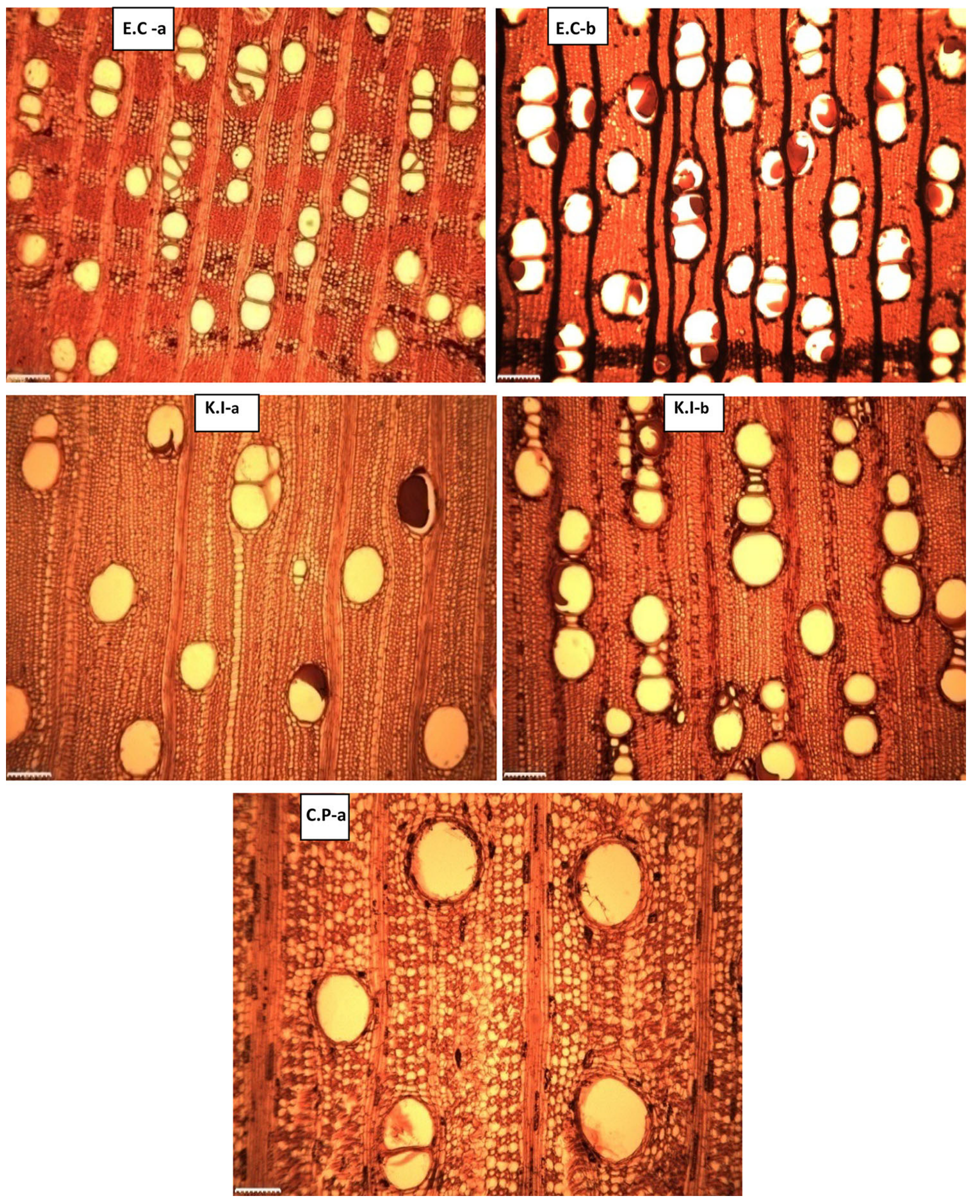


Fig. 2 Transverse sections of the test and control species; *EC Entandrophragma cylindricu*, *KI Khaya ivorensis*, and *CP Ceiba pentandra* Ceiba; *a* stemwood, *b* branchwood. *Scale bar* 200 µm

from branches than wood from the main stem (Haygreen and Bowyer 1996; Stokke and Manwiller 1994; Samariha et al. 2011).

It is also reported that fibres have thicker cell walls and in addition to that in denser woods, the more fibres a wood type/species has, the more it is likely to be durable due to relatively low diffusion of gases that lead to less supply of oxygen for growth and activities of wood biodegraders in such woods (Cartwright and Findley 1958; Haygreen and Bowyer 1996; Rowell 2005). Thus the relatively many fibres in sapele and mahogany wood compared to onyina might have contributed to the significant difference in the percentage weight losses between each of the test species and *Ceiba pentandra* (as recorded in Table 1). In addition, the findings in this study could imply that, comparatively, the relatively higher and lower fibre percentage in sapele and mahogany branchwood in addition to smaller vessel diameters in them as compared to their respective stemwood counterparts appeared not to have translated into natural durability. This is because it was expected that relatively fewer fibres but more voids in branchwood of mahogany compared to stemwood counterparts might have contributed to easy penetration and diffusion of gases for growth and multiplication of biodeterogens, which should have resulted in more significant destruction of the branchwood than the stemwood counterpart (Haygreen and Bowyer 1996). However in this study, the durability of branchwood of mahogany was comparable to its stemwood despite the significant differences in fibre proportions and vessel lumen diameters.

It is however interesting to observe that though the density of sapele branchwood was relatively higher, which is a function of more fibres, than that of its stemwood, yet the durability of branchwood was significantly lower than its stemwood (Table 1). Again, as regards mahogany, although the branchwood density was relatively higher than that of its stemwood, there was no significant difference in their percentage weight losses (natural durability). These trends therefore appear to suggest that some other parameters rather than density and or the selected anatomical properties might have been responsible for the natural durability differences between the branch and stem wood of the species. This therefore appears to corroborate a report that density of wood is not entirely dependent on cell wall thickness and other anatomical properties, but other features such as content of extraneous materials and chemical composition are important (Nzokou et al. 2005; Ncube 2010). As a confirmation, Zabel and Morrel (1992) report that some low density wood species (like western red cedar) have been found to be very durable compared to some high density wood species. Again Eaton and Hale (1993) have also asserted that though the non-nutrient extractives in wood are significantly important in determining decay resistance, density, nitrogen and starch content, and lignin quantity and type can also contribute to the susceptibility of wood to decay. However, these ingredients

Table 3 Summary results on quantitative anatomical properties of stemwood of *Ceiba pentandra* (*onyina*), and stem and branch wood of sapele and mahogany

Species/type of wood	Sapele Mean (SD)	Mahogany Mean (SD)	Onyina Mean (SD)	F Value	p Value
Vessel lumen diameter (µm)					
Stemwood	134.52 (35.37)[a]	144.31 (33.10)[b]	227.21 (35.55)[ab]	107.751	0.000***
Branchwood	124.38 (17.09)	133.52 (29.67)		3.566	0.062*
T Value	1.826*	1.715*			
Vessel proportion (%)					
Stemwood	18.66 (5.55)[a]	15.71 (6.89)[a]	9.38 (3.52)[a]	37.224	0.000***
Branchwood	16.60 (3.17)[c]	19.47 (8.10)[c]		19.433	0.000***
T Value	2.273**	−4.197***			
Fibre proportion (%)					
Stemwood	48.52 (7.58)[a]	53.10 (8.33)[a]	17.69 (5.29)[a]	359.011	0.000***
Branchwood	49.80 (10.72)[c]	45.56 (17.05)[c]		2.219	0.140
T Value	−0.689	2.81***			
Total parenchyma (axial + ray) (%)					
Stemwood	32.82 (8.76)[a]	31.19 (7.39)[b]	72.93 (6.93)[ab]	467.300	0.000***
Branchwood	33.6 (12.05)	32.43 (14.22)		0.195	0.660
T Value	−0.367	−0.550			

Statistical analyses are significant at 95 % confidence level

Mean differences of items with same letters are significant at 5 % significance level

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

that affect the decay resistance of wood occur in varied quantities within tress and among species (Haygreen and Bowyer 1996; Eaton and Hale 1993). Therefore differences in some of these substances between stem and branch woods might have also influenced their durability differences rather than density and the selected anatomical properties.

In another development, it was found that there is a great tendency for insects and pests to attack air-dried wood more than kiln-dried ones (Shrivastava 2000). This, according to Nzokou et al. (2005) might be so because, for kiln-dried wood, the application of heat to the drying process tends to sterilize the wood, kill invisible fungi cells and other invisible biodeterogens that might have entered the wood. This sterilization and its associated effects can delay infestation or re-infestation of wood which consequently could prolong the service life of kiln-dried wood (Nzokou et al. 2005) relative to air-dried ones. In confirmation of this, it is also reported that the method of drying can affect the durability of some wood, and that air-drying could decrease the durability of some wood species to the extent that it can compel reclassification of some wood from a highly resistant or very durable class to a resistant or durable class (Guangxi Universities Forestry College 2007). It is therefore also possible that the air-drying method used to dry the samples as specified in EN 252 (1989) and used for this study might not have helped sapele branchwood to translate its relatively high density into durability relative to its stemwood.

3.3 Relationship between percentage weight loss (natural durability) and wood density

Regression analyses of the relationships between percentage weight loss (%WL) and wood density (kg/m^3) for the species are presented in Fig. 3.

From Fig. 3, as expected, density of stem and branch wood of the species generally correlated negatively with %WL implying positive correlation of density with natural durability (since high %WL imply less durability). The relationships imply that generally, higher density will normally lead to lower percentage weight loss (which depicts higher natural durability) of the wood type. However, the R^2 values indicate that generally, there are strong relationships between density and %WL of both stem and branch woods of the species. But it appears that the relationship is a little stronger for the stemwood ($R^2 = 0.879$ for sapele and 0.965 for mahogany) relative to those of their branchwood ($R^2 = 0.786$ for sapele and 0.972 for mahogany). However, one should not lose sight of the findings that natural durability is not determined by density per se but the anatomical structure of the wood, type and level of extractives, and chemical composition of the wood, all of which build up the density (Haygreen and Bowyer 1996; Nzokou et al. 2005). For this reason some low density wood such as western red cedar is reported to be more durable than some high density ones like beech (Zabel and Morrel 1992; Eaton and Hale 1993).

The generally negative relationships found in this study (Fig. 3) are consistent with some previous studies (Antwi-Boasiako and Pitman 2009; Quartey 2009; Ncube 2010). The R^2 values therefore indicate that density has great influence on decay resistance and agrees with the view that certain wood species are dense and durable or are light and non-durable (Ncube 2010). It is reported that the decay resistance of wood is influenced by density also because, denser wood species are expected to have thicker cell wall substances to be decayed and so such wood can endure deterioration longer than light ones (Zabel and Morrel 1992). Additionally, denser wood tends to be durable because it has relatively fewer vessels with smaller diameters, which limit diffusion of gases and which in turn retard the growth and multiplications of fungus and other biodeteriorating agents on account of diminished supply of oxygen and the accumulation of carbon dioxide around the hyphae of fungi (Cartwright and Findley 1958; Eaton and Hale 1993; Ncube 2010). Relatively fewer vessels with smaller diameters in branchwood appeared to be confirmed in this study especially for sapele (Table 3). But it appeared that the expected effect of such fewer vessels and their smaller diameters on natural durability did not manifest in the branchwood compared to their stemwood counterparts (as observed in Table 1).

3.4 Relationships among anatomical properties, percentage weight loss, visual rating of attack and density of stem and branch wood

Tables 4 and 5 present the correlation matrixes of the relationships among percentage weight loss, visual rating of attack, wood density and the selected anatomical properties for stem and branch woods, respectively. Generally, density had stronger correlation with weight loss (%) and visual rating of attack and most anatomical properties of both stem and branch wood. It should however be noted that the observed correlation between density and natural durability may not be applicable to all wood species, because of type and level of extractives, and lignin type and proportion in wood also appear to offer greater influence on natural durability of wood (Ncube 2010). Thus, there are low density wood species that are more durable than some high density ones due to the chemicals in them. Moreover generally, the anatomical properties had relatively stronger correlation with weight loss (%), visual rating of attack and density of stemwood than the density of their branchwood counterparts (Tables 4, 5). The only exception in this trend

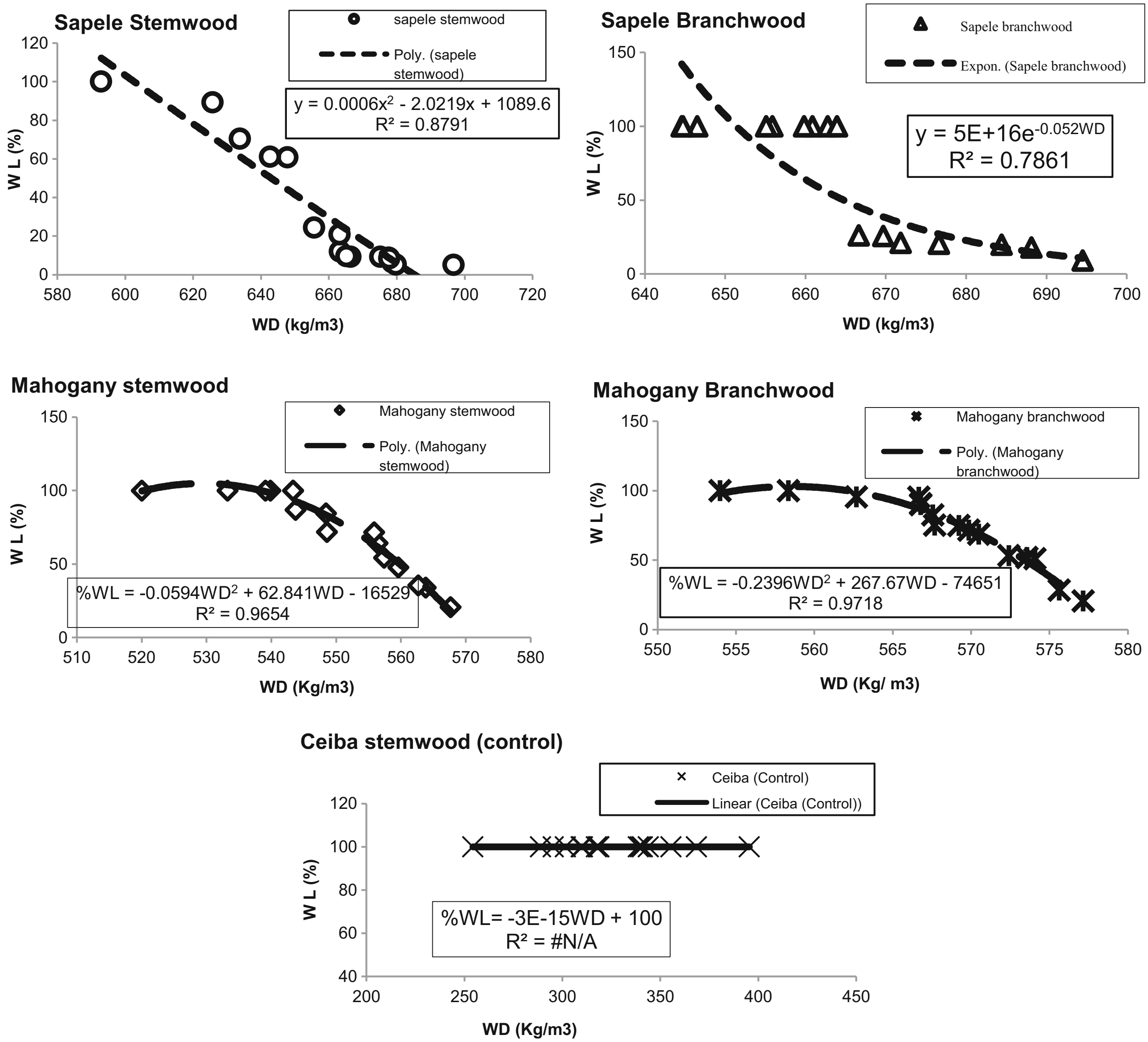


Fig. 3 Relationship between density and percentage weight losses of stem and branch woods of test and control species

is total parenchyma in branchwood. Again in general, density and fibre proportion correlated negatively and significantly with weight loss (%) and visual rating of attack for both stem ($p < 0.01$) and branch wood ($p < 0.05$). This means that higher density and fibre percentage will lead to less weight loss (%) or visual rating of attack, all of which indicate greater resistance of the wood to biodeterioration and therefore greater natural durability. Moreover, whereas in branchwood vessel proportion correlated positively and significantly ($p < 0.01$) with both weight loss (%) and visual rating of attack but negatively with density, it correlated in the opposite with weight loss (%), visual rating of attack and density in stemwood of the species.

The observed relationships (Tables 4, 5) among fibre and vessel proportions with the densities of stem and branch wood found in this study appeared to be consistent with reports in literature that wood with higher fibre percentage and lower proportion of vessels is likely to be denser than that with lower proportion of fibres but higher proportion of vessels (Haygreen and Bowyer 1996; Eaton and Hale 1993). However, vessel lumen diameter, and vessel and fibre proportions also have implications for the porosity, shrinkage, treatability and leachability of wood all of which also affect the natural durability of wood (Haygreen and Bowyer 1996; Desch and Dinwoodie 1996; Tsoumis 1991). The results also appear to agree with findings that in hardwoods, density does not only depend

Table 4 Correlation matrix for the interrelationships among percentage weight loss, visual rating of attack, density and anatomical properties of stemwood of the studied species

Stemwood	Weight loss (%)	Visual rating of attack	Density (Kg/m^3)	Vessel diameter (μm)	Vessel proportion (%)	Fibre proportion (%)	Total parenchyma proportion (%)
Weight loss (%)	1						
Visual rating of attack	0.913**	1					
Density (Kg/m^3)	−0.850**	−0.802**	1				
Vessel lumen diameter (μm)	0.794**	0.674**	−0.844**	1			
Vessel proportion (%)	−0.404**	−0.442**	0.476**	−0.301**	1		
Fibre proportion (%)	−0.612**	−0.450**	0.677**	−0.634**	0.385**	1	
Total parenchyma proportion (%)	0.667**	0.535**	−0.770**	0.624**	−0.642**	−0.955**	1

* $p < 0.01$

** $p < 0.05$

Table 5 Correlation matrix for the interrelationships among percentage weight loss, visual rating of attack, density and anatomical properties of branchwood of the studied species

Branchwood	Weight loss (%)	Visual rating of attack	Density (Kg/m^3)	Vessel diameter (μm)	Vessel proportion (%)	Fibre proportion (%)	Total parenchyma proportion (%)
Weight loss (%)	1						
Visual rating of attack	0.926**	1					
Density (Kg/m^3)	−0.656**	−0.730**	1				
Vessel lumen diameter	0.376*	0.397*	−0.446**	1			
Vessel proportion (%)	0.556**	0.633**	−0.686**	0.152	1		
Fibre proportion (%)	−0.364*	−0.303*	0.505**	0.077	−0.405**	1	
Total parenchyma proportion (%)	0.055	0.055	−0.117	−0.162	−0.067	−0.885**	1

** $p < 0.05$

* $p < 0.01$

on fibre wall thickness but also on the size and amount of void spaces occupied by vessels and parenchyma cells (Wiedenhoeft and Miller 2005). And therefore, when vessels are of large diameters and there is abundance of axial and ray parenchyma, density is likely to be low, and when fibres are in abundance relative to vessels and parenchyma, density is likely to be high (Wiedenhoeft and Miller 2005). Since the void volume is directly related to leachability of toxic compounds (extractives) in wood which also have greater influence on natural durability of wood, vessel lumen diameter also has significant effect on the natural durability of wood (Haygreen and Bowyer 1996; Wiedenhoeft and Miller 2005). Relating to this, it is reported that early colonization of hardwoods by decaying organisms occurs via parenchyma cells and vessels before the fibres attach to vessels and parenchyma (Eaton and Hale 1993). Therefore, wood with many parenchyma and vessels is likely to be deteriorated early. Thus, the larger vessel diameter and the relatively higher percentage of parenchyma cells in onyina stemwood (control species) and mahogany (stem and branch wood) compared to those in sapele (stem and branch wood) might be major contributors to the great destruction of onyina (stem) and mahogany (stem and branch) relative to sapele (stem and branch).

From the correlations of the anatomical properties and density (Tables 4, 5), there also seems to be agreement with reports that opinions are divided regarding the correlations of density with anatomical properties of wood (Sreevani and Rao 2014). For instance, Taylor (1973) reported that density increases with increasing fibre proportion and decreases with increasing parenchyma proportion in *Eucalyptus*, but on the contrary, Sreevani and Rao (2014) found that density of *Eucalyptus* is weakly influenced by fibre proportion and rather increases with increasing parenchyma proportion. In addition, Grzeskowiak et al. (2000) reported positive influence of vessel proportion on density (as has also been found in this study for stemwood) which is also in conflict with the findings by Sreevani and Rao (2014) that density is strongly but rather negatively influenced by vessel percentage, as also found in this study for branchwood. All of this appears to be indicative of the complexity of the relationships existing between wood density and its anatomical characteristics.

4 Conclusion

Density, some selected anatomical properties and natural durability of stem and branch wood of *Entandrophragma cylindricum* (sapele) and *Khaya ivorensis* (mahogany) were assessed in order to ascertain the potential utilization of branchwood of the species as alternatives or supplements to their stemwood for ground and outdoor applications, such as garden furniture and other exposed wooden artefacts. *Ceiba pentandra* (onyina) stemwood served as control. The study also assessed the correlation among natural durability, density and the anatomical properties of stem and branch wood of the species. The natural durability evaluation was based on European Standard EN 252 (1989) in combination with percentage weight losses according to Eaton and Hale (1993) after 12 months of soil block test. Based on the results, the following conclusions were drawn:

1. In general, branchwood of the species exhibited higher density than their stemwood counterparts and the control, which was consistent with previous studies. On the basis of %WL, the natural durability of both the branchwood and stemwood of mahogany were rated non-durable, whereas the branchwood and stemwood of sapele were rated non-durable and moderately durable, respectively. Visual rating of attack showed that both the branchwood and stemwood of mahogany could have similar service lives, whereas branchwood and stemwood of sapele could have different service lives. Branchwood of mahogany can therefore be supplement to its stemwood possibly in similar biological hazard conditions but same cannot be said for the branchwood of sapele. Also in terms of natural durability, branchwood of sapele and mahogany could be extracted for use in applications where *Ceiba pentandra* is being used.
2. Generally, *Ceiba pentandra* exhibited larger vessel diameter than stemwood and branchwood of the test species. Vessels in branchwood were significantly smaller than those in stemwoods ($p < 0.1$) and their quantities were lower in branchwood of sapele but higher in branchwood of mahogany. Whereas total parenchyma was comparable in stem and branchwood of both test species, fibre proportion was comparable in stem and branch wood of only sapele but it was significantly lower in branchwood than stemwood of mahogany ($p < 0.01$). All of the selected anatomical properties of the test species were significantly different from those of the control species (*Ceiba*) ($p < 0.01$).
3. For the studied species, it appears that the general notion that the higher the density the higher the natural durability (i.e. lesser percentage weight loss and visual rating of attack) of the wood is true to some extent but not entirely, since though density correlated negatively with percentage weight loss, the correlations were not linear. The influence of vessel lumen diameter, and vessel, fibres and parenchyma proportions on natural durability and density were stronger and significant ($p < 0.01$) in stemwood than in the branchwood of the species studied. However generally, in both stem and branch wood, fibre proportion influenced natural durability and density positively, whereas vessels lumen diameter and total parenchyma proportion influenced natural durability and density negatively.

On the basis of the foregoing, the following recommendations are made;

1. The branchwood of the species should be taken through other property tests such as mechanical strength, extractive content, and resistance to physical and chemical deterioration tests and even durability test at different sites in comparison with their respective stemwood in order for a more conclusive statement to be made regarding their applications for better acceptance and use.
2. Stem and branch wood of mahogany and the branchwood of sapele may need treatments with preservatives to improve their service lives, if it becomes so necessary to use them for ground or outdoor applications.
3. Further studies on fibre dimensions, reaction and juvenile wood contents in branchwood compared to their stemwood counterparts should be carried out to ascertain their influence on density.

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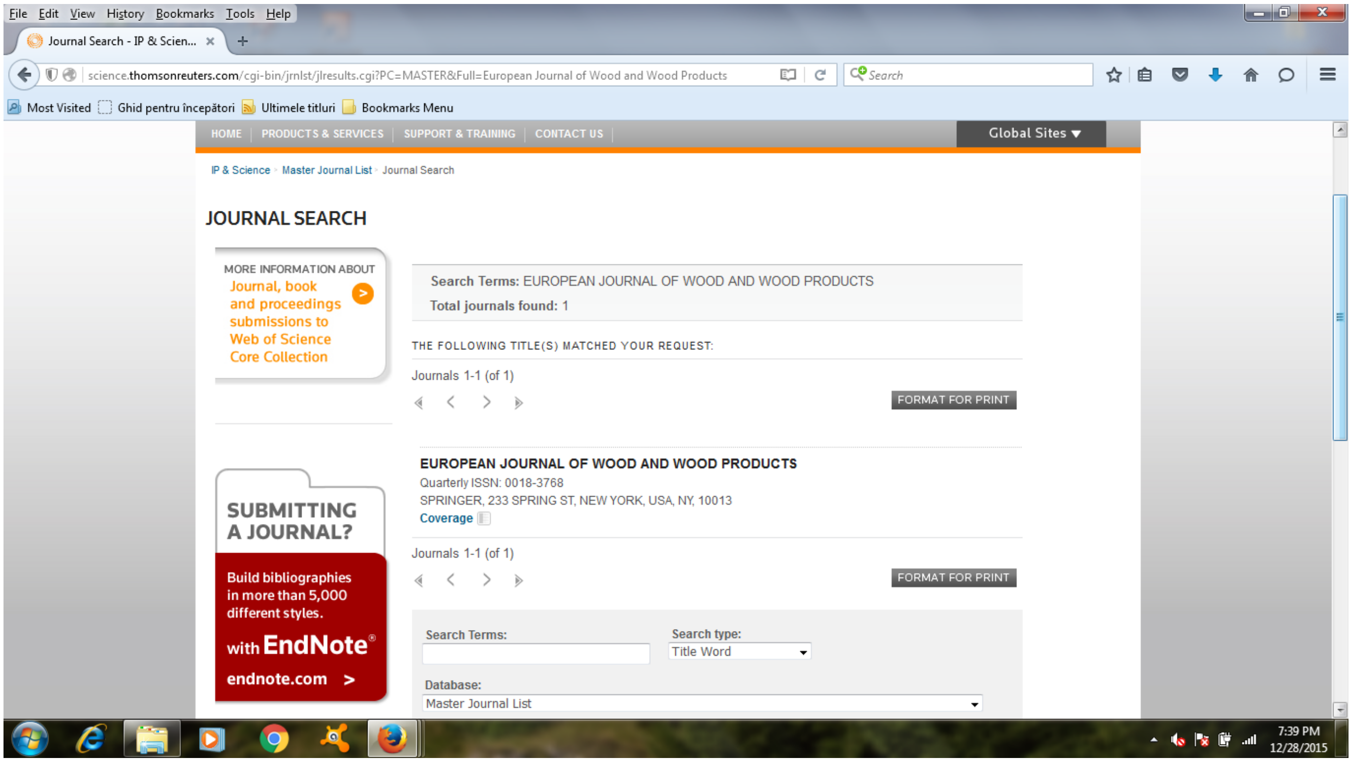
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